SEMI-ANNUAL REPORT ON

RESEARCH IN ELECTROHYDRODYNAMICS AND

TRAVELING-WAVE ELECTROMECHANICAL ENERGY CONVERSION

NASA Grant No. NsG-368

Covering the Period:

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Supervised by:

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Semi-Annual Report on
Research in Electrohydrodynamics and
Traveling-Wave Electromechanical Energy Conversion

NASA Grant NsG-368

I Introduction and Status of Research

This report summarizes current research for the period 1 August, 1966, through 31 January, 1967, sponsored under the NASA Grant NsG-368. It is supplemented by the following preprints and informal reports which are either submitted with this report or have previously been sent to NASA.

Preprints:

"Hydromagnetic Surface Waves with Alternating Magnetic Fields", M. J. Schaffer, M.I.T. Center for Space Research Report CSR TR-66-11.

"Traveling-Wave Bulk Electroconvection Induced Across a Temperature Gradient", J. R. Melcher and M.S. Firebuagh, M.I.T. Center for Space Research Report CSR TR-66-13.

Informal Reports and Theses:

"Stability of a Distributed Parameter System Controlled by Spatially and Temporally Sampled Feedback", R. H. Thomas, M.S. Thesis, 1966.

"Theory of Thermally Induced Electroconvection", R. J. Turnbull, Internal Memo. No. 126, Continuum Electromechanics Group, M.I.T.

"A Note on the General Solution of a Two-Dimensional Biharmonic Equation", C. V. Smith, Jr., Internal Memo. No. 125, Continuum Electromechanics Group, M.I.T.

"A Theorem for Charge Relaxation in Electrohydrodynamics", C. V. Smith, Jr., Internal Memo No. 124, Continuum Electromechanics Group, M.I.T.

"Temperature Measurement of an Equilibrium Plasma by Means of a Pressure Transducer", T. B. Jones, Jr., Internal Memo. No. 127, Continuum Electromechanics Group, M.I.T.

Also included for general information are the following reprints:

"Continuum Feedback Control of Instabilities on an Infinite Fluid Interface", Physics of Fluids, 9, No. 10, October 1966.

"Traveling Wave Induced Electroconvection", Physics of Fluids, 9, No. 8, August, 1966.

This report follows a format used in previous progress reports. It is divided into two sections, the first of which is concerned with research on the continuum electromechanics of field-coupled systems, with emphasis on electrohydrodynamics. The second section presents work on traveling-wave electromechanical energy conversion.

The contents of this semi-annual report are supplemented by the "Proposal to NASA for A Renewal of NASA Research Grant NsG-368 for Research in Continuum Electromechanics With Emphasis on Electrohydrodynamics and in Magnetohydrodynamic A-C Power Generation for the Period February 1, 1967, to January 31, 1968". That document includes a "state of the art" summary of our overall pattern of research activity. This makes it possible to limit this report to a brief summary of the current status of research.

List of Topics Together with Present Status of Research

Sec. of Report	Topic	Status
IIA-a	An Electrohydrodynamic Induction Flow-Meter (Charge Relaxation On a Moving Liquid Interface.)	To be published, Physics of Fluids, Feb. 1967.
IIA-b	Electrohydrodynamic Induction Bulk Interactions (Traveling-Wave Bulk Electroconvection Induced Across a Temperature Gradient.)	Submitted for pub'n to Physics of Fluids. Preprint sent NASA. Paper presented at Stanford U APS Mtg.

IIA-c	Electrohydrodynamic Relaxation Surface Instabilities.	Experimental work continues
IIA-d	Containment of Dielectric Fluids with Rotation	Experimental and theoretical work now underway as M.S. Thesis
IIA-e	Effect of D-C Bias on an A-C Orientation of Dielectric Liquids.	Experiment & theory in final stages; paper presented at Stanford APS Mtg.
IIA-f	Electromechanical Co-streaming and Counterstreaming Instabilities.	Submitted for pub'n. in Physics of Fluids
IIA-g	Electromechanical Stream-Structure Instability	Submitted for pub'n. Physics of Fluids
IIA-h	Thermally Induced Electrohydynamic Bulk Instability	Exp. and theoretical work in progress as Ph.D. thesis; report sent to NASA.
IIA-i	Static Field-Gradient Electroconvection	Experimental & theoretical work in progress as PhD. Thesis
IIA-j	Surface Magnetohydrohynamics with High-Frequency Magnetic Fields.	Ph.D. thesis compl'd. Preprint sent NASA. To be submitted for pub'n to Phys. Fluids
IIA-k	Bang-Bang Surface Interactions with a Static Fluid.	Experimental work in progress as M.S.thesis
IIA-l	Field Gradient Stabilization of Kelvin-Helmholtz Instability (including Bang-Bang stabilization).	Theory partially developed; experimental work in design stages of B.S. Thesis
IIA-m	Bulk Gradient Stabilization	Experiment & theory partially developed; B.S. Thesis

IIB-a	Continuum Feedback Control of a Rayleigh-Taylor Type Instability	Published, Phys. of Fluids, Nov. 1966.
IIB-b	Continuum Feedback Control of Instabilities on an Infinite Fluid Interface.	Published, Phys. of Fluids, Oct. 1966
IIB-c	Electrostatic Levitation of Liquids	Project reactivated as B.S. Thesis
IIB-d	Continuum Feedback Control of Rayleigh-Taylor Type Instability Using Video Sampling Techniques.	Ph.D. Thesis undertaken; experiment presently in planning stage.
IIB-e	Stability of a Distributed Parameter System Controlled by Spatially and Temporally Quantized Feedback.	M.S. Thesis completed; sent to NASA as preprint in preparation.
III - a	Excitation and Detection of Magnetoacoustic Waves in a Rotating Plasma.	Work summarized in artic[le] in process of pub'n in AIAA Journal.
III - b	Wave-Type MHD A-C Power Generation	Experiment in progress to show wave-structure interaction; Inf. report incl. with this report.
III - c	Synchronous, Traveling-Wave Electrohydrodynamic Power Generation	Three M.S. Theses currently in initial stages

I. Continuum Electromechanics of Field-Coupled Systems

Personnel:

J. R. Melcher, Associate Professor

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E. B. Devitt, Teaching Assistant (Ph. D. candidate)

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Miss R. Goldstein (B.S. candidate)

R. Landley (B.S. candidate)

G. Blankenship (B.S. candidate)

A. Basic Investigations of Field-Coupled Waves and Instabilities

We consider the areas of research outlined in Sec. I in the order listed.

1) An Electrohydrodynamic Induction Flow-Meter (Charge Relaxation on a Moving Liquid Interface)

An article summarizing this work will be published in the February 1967 issue of Physics of Fluids. Galley proofs have been returned. Future work concerned with natural conduction phenomena will make use of either the apparatus used in these experiments, or of a second generation of this apparatus, refined so that a lesser quantity of fluid would be required to make a conductivity measurement.

Patent research is currently being undertaken by the M.I.T. patent office.

2) Electrohydrodynamic Induction Bulk Interaction
Preprint of this work has been submitted to NASA as MIT Center for Space Research report CSR-TR-66-13, and submitted for publication to Physics of Fluids. Patent investigation currently being initiated by M.I.T. patent office.

3) Electrohydrodynamic Relaxation Surface Instabilities
Experiments have been conducted to measure the voltage (rms) for instability on an interface between fluids having relaxation frequencies on the same order as the frequency of the applied voltage. This data was taken over a range of frequencies where parametric forms of instability could be ruled out. Currently, efforts are being made to extend previous theoretical developments to predict these experimental results.

4) Containment of Dielectric Fluids with Rotation
Although considerable theoretical and experimental work on the electrohydrodynamics of rotating fluid systems has been done previously under NsG-368, none of this work has reached a stage where it has been reported in the open literature. Several projects are planned and under construction in this area at present, and are the basis for an M.S. thesis. These relate to studies of the basic field interactions with the fluids in rotation. The nature of the experiments was described in Part II-E of the proposal submitted previously.

5) Effect of D-C Bias on A-C Orientation of Dielectric Liquids
In this project, we show how a simple superposition model can be used to predict the stability of combined a-c and d-c systems. A paper was presented at the annual meeting of the

American Physical Society on this subject, Nov. 23, 1966. The abstract of that paper is as follows:

Free-Charge Instability of a Dielectrophoretically Oriented Fluid

by

F. D. Ketterer and J. R. Melcher

If two slightly-conducting immiscible liquids of equal density are placed in the annulus between concentric circular electrodes having an a-c potential difference, the liquid of higher permittivity can be oriented around the inner electrode. The potential must have a frequency which is much larger than the reciprocal relaxation time for free charge in either of the fluids. The effect of an additional d-c potential is studied in the case where the inner fluid is much more highly-conducting than the outer fluid, so that free charge can relax to the interface. A simple analytical model predicts the d-c potential for instability as a function of the a-c potential and physical parameters. The a-c fields are assumed to interact at the interface as though both fluids were perfectly insulating. At the same time, the d-c fields are assumed to be excluded from the inner fluid, which acts as a perfect conductor and interacts with the d-c field at the interface through free surface charges. Experiments have been carried out verifying features of the theory.

Experiments indicate some correlation with theory, but also show effects that had not previously been observed. It is found that experiments show marked effects from the polarity of the d-c potential. In addition, if the d-c potential is kept in the same polarity over a long period of time, [illegible] instability drift with time. For example, in an experiment involving silicon oil and corn oil, the d-c potential for instability has been found to decrease steadily over a period of two hours, from an initial value of 4 kv to less than 2 kv. These results indicate a surface phenomenon which deserves further investigation. Since the effect is sensitive to polarity, it is presently felt that it might be due to electrophoretic forces at the interface, created by ions emitted from one of the electrodes.

6 & 7) <u>Electromechanical Co-Streaming and Counterstreaming Instabilities and Electromechanical Stream-Structure Instability</u>

Preprints having these titles have been submitted to NASA previously; these articles have been submitted for publication to <u>Physics of Fluids</u>.

8) <u>Thermally Induced Electrohydrodynamic Bulk Instability</u>

This category of experiments is aimed at developing a basic knowledge of convective heat transfer in electric fields, either with a view toward augmenting the heat transfer or to thermally pumping a fluid. Progress in the fundamental types of instability found in this class of interactions is summarized in the attached internal Memorandum No. 126. This activity has an immediate application in the space program, since electric fields are now being proposed as a means of producing a uniform-temperature cryogenic liquid in zero-gravity environments. In space, where fuel tanks are subject to various types of heat flux from the boundaries, the venting of cryogenic storage systems is largely determined by the hot spots of the system. Venting becomes far less of a problem if the temperature rise can be evenly distributed throughout the liquid. However, the main physical mechanism for bringing this about in earth-bound systems is variation in density (produced by the temperature gradient) interacting with gravity. In space, where there is no gravity, the hot spot problem becomes extra critical. Electric fields, interacting with the liquid through the basic mechanism described in this work, provide a means of inducing thermal (electro)convection and wiping out the temperature gradients.

Our fundamental work in this area is being communicated to the people interested in developing this application. As with earlier work we have done, with its impact on the cryogenic orientation program, one of our main functions has been to establish the correct physical picture of the interactions responsible for the induced electroconvection. This area is no exception in the trend of those people who have given attention to heat transfer systems in electric fields to use the wrong force density.

9) Static Field-Gradient Electroconvection

Theoretical aspects of this problem were communicated to NASA previously, in the form of an informal report entitled: "An Electrohydrodynamically-Induced Spatially Periodic Stokes-Flow". During the past quarter, an experiment has been conducted which displays, in classic simplicity, the cellular convection induced by an electric field through a surface interaction. This cellular motion is being filmed, both to show the basic interaction and to obtain data which will be correlated with the theory. This project has the basic objective of showing how cellular convection can be used to produce energy conversion and enhanced heat transfer A Ph.D. thesis should be completed by Sept. 1967.

10) Surface Magnetohydrodynamics with High Frequency Magnetic Fields

A preprint summarizing this activity during the last six months has been sent to NASA as Center for Space Research report

CSR TR-66-11, with the title: "Hydromagnetic Surface Waves with Alternating Magnetic Fields".

11) Bang-Bang Surface Interactions with a Static Fluid

This project was described under part II-C-2 of the Quarterly Progress Report (including the proposal for renewal of support, sent November 10, 1966) referred to in the Introduction. Three experimental activities are now underway, and represent the basis for two M.S. theses and a B.S. thesis. A 400-cps high voltage system has been constructed and tested. This has been used to demonstrate indefinite orientation of liquids like corn oil over air by using the bang-bang stabilization of the "upside down" interface. Our investigations are presently divided into three categories:

1. Measurement of the marginal conditions for instability and the development of an appropriate theory. This theory will probably be linear, and somewhat similar to that used in the gradient stabilization systems.
2. Measurement of the large-amplitude "sloshing" characteristics of the equilibrium, with the bang-bang used both to orient the fluid against an adverse acceleration, and to prevent sloshing of an interface.
3. Measurement of the conditions for parametric instability, as they depend on the frequency of the applied voltage. The 400 cps system was constructed so that the first two classes of experiment could be conducted without being concerned with the third class of problem. With 60 cps high voltage used in an experiment involving liquids having the viscosity of water, parametric instability imposes a significant limitation on what can be achieved with the bang-bang interaction.

12) Field Gradient Stabilization of Kelvin-Helmholtz Instability

This project was described in Sec. II-D-1 of the Quarterly Report. It is currently in the initial stages of experimental activity, and is the subject of a B.S. thesis. Our first objective is to demonstrate the Kelvin-Helmholtz instability in an apparatus having essentially two-dimensional flow conditions.

13) Bulk Gradient Stabilization

Sec. II-F-2 of the Quarterly Report described this project, which is currently being developed as a B.S. thesis. The apparatus has been partly constructed, and a theoretical model for the instability conditions is available. It is hoped that we will be able to film the bulk instability, since there is no precedent for its observation.

B. Continuum Feedback Control of Electromechanical Systems

1. Continuum Feedback Control of a Rayleigh-Taylor Type Instability
This work was the subject of an article published in the November, 1966, issue of Physics of Fluids. Reprints included here.

2. Continuum Feedback Control of Instabilities on an Infinite Liquid Interface
This project involved the development of a new technique for analyzing continuum systems subject to spatial sampling and feedback. It was the subject of an article published in the October, 1966, issue of Physics of Fluids. Reprints included.

3. Electrostatic Levitation of Liquids
This project is being reactivated. It was described in Sec. II-D of the proposal for continuation of NsG-368 for the period Feb. 1, 1966 to Jan. 31, 1967 and is currently the subject of a B.S. thesis. The equipment is mostly constructed, but so far there has been no experimental activity.

4. Continuum Feedback Control of Rayleigh-Taylor Type Instability Using Video Sampling Techniques.

As has been pointed out in many previous reports and publications, our most significant objective in the area of continuum feedback control is to demonstrate experimentally and theoretically that an electronic continuum can be realized which will interact with a mechanical continuum on a continuum basis. This then makes it possible to control the dynamics of continuous media by using the electronic continuum for feedback purposes.

It is clear from the outset that if this objective is to be realized, video systems must be employed. Our past experimental and theoretical work places us in a position to design a video system now which will reach our objective. In this phase of this research, attention will be confined to continua that involve essentially a dependence on one spatial variable. The design of an experiment is currently underway, and will be the basis for a Ph.D. thesis.

5. Stability of a Distributed Parameter System Controlled by Spatially and Temporally Quantized Feedback

This work was the subject of an M.S. thesis, copies of which were submitted to NASA previously. It is currently being summarized in preprint form, and will be submitted for publication.

III. Traveling-Wave Electromechanical Energy Conversion

Personnel:

G. L. Wilson, Assistant Professor of Elec. Engineering (currently on leave of absence)
J. R. Melcher, Associate Professor of Electrical Engineering
T. B. Jones, Jr., M.S. candidate and N.S.F. Fellow
L. Herrold, Cdr., U.S. Navy, M.S. candidate
[illegible] candidate
[illegible]

A. Excitation and Detection of Magnetoacoustic Waves in a Rotating Plasma

This work was summarized in a preprint previously sent to NASA; it has been accepted for publication in the Journal of the AIAA.

B. Wave-Type MHD A-C Power Generation

This was described in Sec. III A of the Quarterly Report sent in November. Experimental work is presently in progress. An informal report relating to this activity is included here, entitled: "Temperature Measurement of an Equilibrium Plasma by Means of a Pressure Transducer".

C. Synchronous, Traveling-Wave, Electrohydrodynamic Power Generation

Three M.S. theses are currently in progress on this subject. The basis for this activity was described in Sec. II-B-2 of the Quarterly Report sent last fall. A small wind tunnel is currently being checked out. Initial tests of the charge induction process should begin within two weeks, and tests of the synchronous interaction will start within the month.

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